Beat-note interferometer for direct phase measurement of photonic information

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We describe a simple method of the beat-note interferometer that directly and dynamically measures the phase shift of light pulses induced by highly dispersive samples. Using the method, we show intuitively that the storage and retrieval of light pulses in a medium due to the effect of electromagnetically induced transparency is a coherent process and, quantitatively, that there is no observable phase shift caused by the process. This method is sensitive enough that it can be used to measure the phase of a light pulse with energy on the order of a dozen photons.

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Phase is the fundamental information carried by light pulses which can be employed as carriers from quantum logic gates to quantum memory or as qubits in quantum computation [1–6]. Highly dispersive media, such as narrow atomic transitions, optical cavities, and so on, are often considered as potential tools to manipulate the phase of light pulses [7–9]. Here we describe a simple, direct, and dynamic method to measure the phase shift of light pulses induced by highly dispersive samples. Our method is able to study phase evolution from head to tail of the probe pulse in the light-storage experiment and to measure the phase shift of the probe field as a function of time in the transient electromagnetically induced transparency (EIT) experiment. Using this method, we successfully measured the phase of a Gaussian pulse with a peak power of 400 pW. The data obtained indicate that the proposed method can be used to study light pulses with energies on the order of a dozen photons. This method should make possible new and exciting experiments that will advance our knowledge in the relevant research fields.

Inspired by the Mach-Zehnder interferometer, we used the method depicted in Fig. 1 to measure the phase shift of light pulses induced by a highly dispersive sample. In this system, a laser beam is passed through an acousto-optic modulator (AOM) and the zeroth- and first-order output beams of the AOM are spatially recombined by a 50-50 beam splitter (BS) cube. The driving frequency ω_a of the AOM is sufficiently large that the interaction between the zeroth-order beam and the sample is negligible whereas the first-order beam probes the sample's dispersive profile. Two beams emerge from the beam splitter cube: beam 1 is directly received by a photodetector (PD1), and beam 2 is received by another detector (PD2) after propagating through the sample. Both beams carry beat notes at the frequency of ω_a. The signals from the two detectors are proportional to $E_z^2+E_f^2+2E_zE_f\cos(\omega_a t+\phi_r)$ and $E_z^2+E_f^2+2E_zE_f\cos(\omega_a t+\phi_p+\Delta\phi)$, where E_z and E_f are the amplitudes of the zeroth- and first-order output beams of the AOM, respectively. In this case, E_z is a constant and E_f describes the slowly varying envelope of a pulse. ϕ_r and ϕ_p are the phases that result from the optical paths, the AOM switching, or other factors. Although ϕ_r and ϕ_p vary from one pulse to another, their difference is always fixed. $\Delta\phi$ is the phase shift induced by the sample; it is directly measured by comparing the two beat notes in the oscilloscope. The above method for measuring the phase shift is denoted as the beat-note interferometer and is surprisingly immune to position changes of optics or variation of the optical path. The advantage of such immunity enables us to measure phase shifts contributed only by samples.

We applied the beat-note interferometer to cold ^{87}Rb atoms produced by a vapor-cell magneto-optical trap (MOT). Typically, we trapped 10^9 atoms in the MOT, as measured by the optical-pumping method [10]. The coupling and probe fields in the experiment drove the $|5S_{1/2},F=2\rangle\rightarrow|5P_{3/2},F'=2\rangle$ and $|5S_{1/2},F=1\rangle\rightarrow|5P_{3/2},F'=2\rangle$ transitions, respectively. They formed the Λ-type configuration of EIT. Details of the two laser fields and the measured EIT spectrum can be found in Ref. [11]. The present experiment differed from that described in Ref. [11] in one aspect. In the previous study, the high-frequency sideband of the 6.8-GHz electro-optic modulator (EOM) output directly seeded the probe laser. In the present work, however, the probe laser was injection locked by an intermediate laser seeded with the EOM output; this arrangement completely removed the influence of the carrier of the EOM output. The relaxation rate of the ground-state coherence in our system was about 0.002Γ, as estimated from the spectrum, where $\Gamma=2\pi\times5.9$ MHz is the spontaneous decay rate of the excited states. The probe beam passed through the AOM shown in Fig. 1 to form the beat-note interferometer. We generated pulses of the first-order beam by controlling the rf power of the AOM. The zeroth-order beam was always present, but had little effect on the atoms.

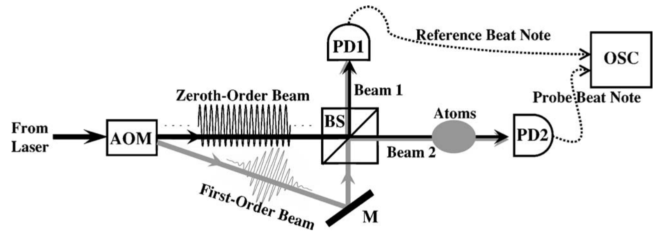

FIG. 1. Schematic of the beat-note interferometer. PD, photodetector; BS, beam splitter cube; M, mirror; OSC, oscilloscope.

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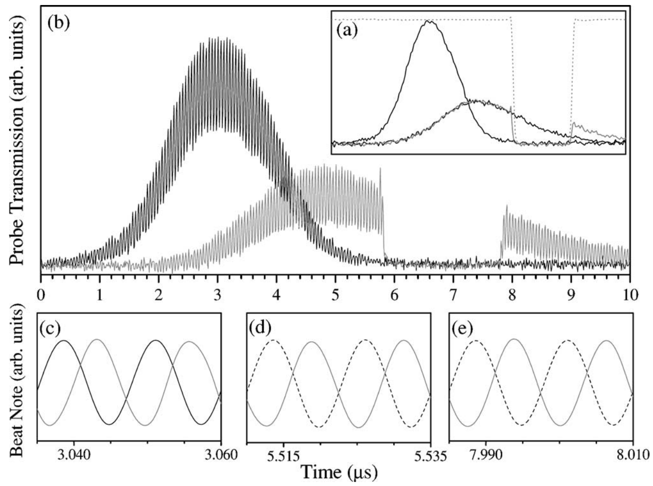

FIG. 2. Storage and retrieval of the light pulse. (a) The zeroth-order output beam of the AOM is blocked. Black lines are the data from PD1 and PD2 under the condition that the coupling field be constantly present. The gray line also indicates the signal from PD2, but under the condition that the coupling field (dotted line) be switched off momentarily. (b) The reference and probe beat notes from PD1 (black) and PD2 (gray). (a) and (b) have the same horizontal axis. (c), (d), and (e) show different parts of the two beat notes. Dashed lines in (d) and (e) are extrapolated from the reference beat note in (c).

Throughout the entire experiment, the power of the zeroth-order beam was 2 μW and ω_a was $2\pi\times 80$ MHz. All the laser and magnetic fields of the MOT were turned off during the phase measurement. Signals from the photodetectors (New Focus 1801) were averaged 256 times by the digital oscilloscope (Tektronix TDS 320) before being transferred to the computer.

The probe pulse can be completely halted in the atoms by adiabatically switching off the coupling field and can be subsequently released intact by the reverse process [12–15]. Figure 2 shows data for a representative example of this intriguing ability to store and retrieve the probe pulse. The Rabi frequency of the coupling field, Ω_c, is 0.35Γ and that of the peak of the probe pulse, $\Omega_{p,max}$, is 0.1Γ. Both fields are tuned to their resonance frequencies. Figure 2(a) shows the data under the condition that the zeroth-order output beam of the AOM be blocked. The two black lines of large and small pulse amplitudes are the signals from PD1 and PD2, respectively, when the coupling field is constantly present. The delay time between the two pulses is about 1.7 μs due to the reduction of group velocity in the EIT medium. The gray line also depicts the signal from PD2, but under the condition that the coupling field be switched off momentarily, as indicated by the dotted line. This switching occurs at the moment that part of the pulse has left the atoms, shown as the part of the gray line overlapping with the black line. The remainder of the pulse is stored in the atoms. During the storage period, PD2 receives no signal and there is a gap in the gray line. After the coupling field has been absent for 2.0 μs, it is switched back on. The stored pulse is released from the atoms, leading to the reappearance of the signal from PD2 (the right part of the gray line).

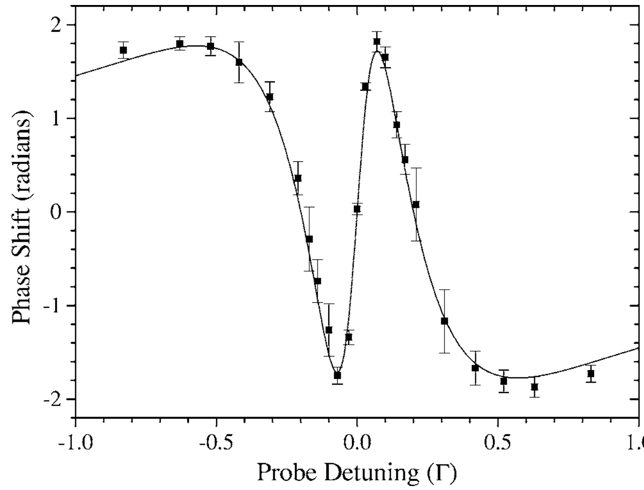

FIG. 3. Phase shift of the probe field versus the probe detuning in the EIT condition. Squares are the experimental data and the solid line is the theoretical prediction.

The storage and retrieval of the probe pulse described above is a coherent process [16,17]. This is demonstrated intuitively in Fig. 2(b) with the beat-note interferometer. The black and gray beat notes are the signals from PD1 and PD2, respectively. If the phases of the incoming and outgoing waves of the storage are uncorrelated, there is no beat signal in the retrieved pulse. The phases in different parts of the probe pulse were quantitatively examined, as shown in Figs. 2(c)–2(e). We triggered the oscilloscope by the reference beat note. A rf switch (Mini-Circuits ZFSWHA-1-20) was employed to select the Gaussian peak, and its output provided the trigger signal. The oscilloscope waited a certain delay time and then acquired data from the two detectors. We found the instability of a 1-ms delay of the oscilloscope to be equivalent to a phase jitter of $\pm 1.5°$ at the beat frequency of 80 MHz. The driving frequency of the AOM or the beat frequency is sufficiently stable that we are able to extrapolate the reference beat note in Figs. 2(d) and 2(e). Within the measurement accuracy, the phase of the retrieved wave perfectly evolves from the incoming wave and there is no observable phase jump caused by the switching process.

We measured the phase shift of the probe field induced by the atoms in the EIT condition. Figure 3 shows the experimental data and theoretical prediction for the variation in the phase shift as a function of the probe detuning. The coupling field drives the transition resonantly and the probe field is a 10-μs-square pulse with $\Omega_p=0.1\Gamma$. The phase shift data were taken near the end of the pulse to ensure that the transient effect was negligible. The zeroth-order beam that reaches PD2 has a Rabi frequency of 0.1Γ and induces a negligible light shift of $3.7\times 10^{-4}\Gamma$ to the probe transition frequency. In the theoretical prediction of a Λ-type three-state EIT system, we used the following experimentally derived values: $\Omega_c=0.40\Gamma$, optical density of the atoms$=7.1$, and relaxation rate of the ground-state coherence$=0.002\Gamma$ [11,18]. Around the EIT window, where the laser linewidth is irrelevant due to the phase lock between the coupling and probe fields, the consistency between the experimental data and the theoretical prediction is satisfactory. Away from this window, however, the experimental and theoretical plots deviate because the laser linewidth is not considered in the calculation. With our method, it is possible to measure the phase evolution of the probe field for the study of the transient EIT. In contrast, most previous experimental studies of transient EIT have provided only data on the amplitude evolution of the probe field [19–21]. The present method thus opens the way to explore the transient behavior of the probe phase.

Below we list some additional noteworthy features of the beat-note interferometer for phase measurement. (i) Fluctuation of the optical paths from the AOM to the BS does not affect the difference between ϕ_r and ϕ_p and, hence, does not degrade the measurement accuracy and repeatability of $\Delta\phi$. (ii) Fluctuation of the optical paths from the BS to the two detectors results in noise or fluctuation of the $\Delta\phi$ measurement. Nevertheless, the phase change per unit length is only ω_a/c or 1.7×10^{-3} rad/mm. (iii) Since $\Delta\phi$ is measured by directly comparing the two beat notes, the measurement value is almost independent of the laser power. (iv) All the pieces of equipment employed in the phase measurement method are general-purpose products. (v) Using the proposed method, we measured the phase shift induced by the atoms in the EIT condition for a Gaussian pulse with the peak power of 400 pW, as shown in Fig. 4. With a photodetector with a larger gain (e.g., 2.5×10^5 V/W for Thorlabs APD-210), it is feasible to perform the phase measurement of a pulse with a width of 0.1 μs and energy of 14 photons. In principal, the sensitivity could be further improved by increasing the power and intensity of the zeroth-order beam, although we were unable to do this with the current setup. (vi) Two beams from different lasers can replace the zeroth- and first-order beams of the AOM. The two lasers are phase locked with an arbitrary frequency difference—e.g., 9 GHz in Ref. [22]. This arrangement can make our method applied to broader research subjects.

In conclusion, we have shown intuitively that the storage and retrieval of light pulses is a coherent process and, quantitatively, that there is no phase jump caused by the switching of the coupling field. The measured phase shift induced by the EIT sample is in good agreement with the theoretical prediction. Our measurement system makes possible the study of the phase evolution of the transient EIT. The beat-note interferometer is a simple, direct, dynamic, robust, and sensitive method for studying the phase shift of light pulses induced by highly dispersive samples.

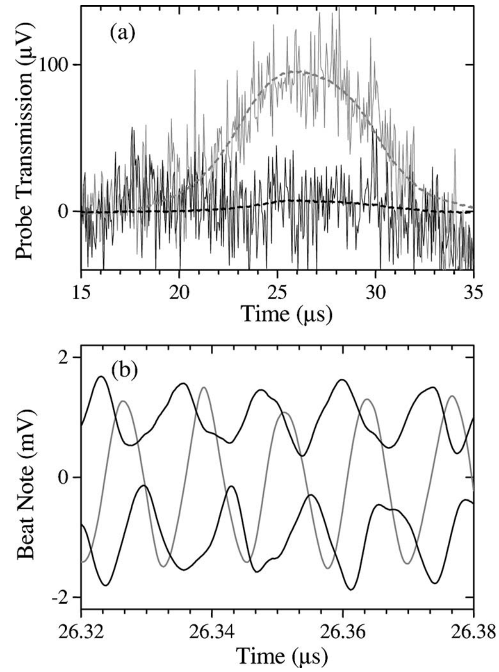

FIG. 4. Phase measurement of weak probe pulses. $\Omega_c=0.40\Gamma$, $\Omega_{p,\max}=6.5\times10^{-3}\Gamma$, and Δ_p(probe detuning)$=\pm0.05\Gamma$. The gain of the photodetector is 2.5×10^4 V/W. (a) The zeroth-order output beam of the AOM, 1 μW of which reaches PD2, is blocked. Gray and black solid lines are the probe transmissions in the absence and presence of the atoms; the peak powers of these transmissions are about 4 and 0.4 nW, respectively. To guide the eye, dashed lines depict the experimental data recorded at a much higher power. (b) The beat notes at the two probe detunings are compared to that without the atoms. The measured phase shifts of -1.5 ± 0.5 and 1.8 ± 0.4 rad are in agreement with the predicted values.

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